# Structure Formation with Mirror Dark Matter: CMB and LSS

Zurab Berezhiani [a,b,1], Paolo Ciarcelluti [a,2], Denis Comelli [b,3], Francesco L. Villante [b,c,4]

[a] *Dipartimento di Fisica, Università di L'Aquila, 67010 Coppito AQ, and INFN, Laboratori Nazionali del Gran Sasso, 67010 Assergi AQ, Italy*
[b] *INFN, sezione di Ferrara, 44100 Ferrara, Italy*
[c] *Dipartimento di Fisica, Università di Ferrara, 41000 Ferrara, Italy*



**Abstract**

In the mirror world hypothesis the mirror baryonic component emerges as a possible dark matter candidate. An immediate question arises: how the mirror baryons behave and what are the differences from the more familiar dark matter candidates as e.g. cold dark matter? In this paper we answer quantitatively to this question. First we discuss the dependence of the relevant scales for the structure formation (Jeans and Silk scales) on the two macroscopic parameters necessary to define the model: the temperature of the mirror plasma (limited by the Big Bang Nucleosynthesis) and the amount of mirror baryonic matter. Then we perform a complete quantitative calculation of the implications of mirror dark matter on the cosmic microwave background and large scale structure power spectrum. Finally, confronting with the present observational data, we obtain some bounds on the mirror parameter space.

## 1 Introduction

The idea that there may exist a hidden mirror sector of particles and interactions with exactly the same properties as that of our visible world was suggested long time ago [1]. The basic concept is to have a theory given by the product $G \times G'$ of two identical gauge factors with the identical particle contents, which could naturally emerge e.g. in the context of $E_8 \times E'_8$ superstring. (From now on the "primed" ($'$) fields and quantities stand for the mirror (M) sector to distinguish from the ones belonging to the observable or ordinary (O) world.) In particular, one can consider a minimal symmetry $G_{\rm SM} \times G'_{\rm SM}$ where $G_{\rm SM} = SU(3) \times SU(2) \times U(1)$ stands for the standard model of observable particles: three families of quarks and leptons $q_i,\ u^c_i,\ d^c_i;\ l_i,\ e^c_i$ $(i = 1, 2, 3)$ and the Higgs doublet $\phi$, while $G'_{\rm SM} = [SU(3) \times SU(2) \times U(1)]'$ is its mirror gauge counterpart with analogous particle content: fermions $q'_i,\ u'^c_i,\ d'^c_i;\ l'_i,\ e'^c_i$ and the Higgs $\phi'$. The M-particles are singlets of $G_{\rm SM}$ and vice versa, the O-particles are singlets of $G'_{\rm SM}$. More generally, one can have in mind the grand unified extensions like $SU(5) \times SU(5)'$, $SO(10) \times SO(10)'$, etc. Besides the gravity, two sectors could communicate by other means [2]. In particular, ordinary and mirror neutral particles could mix: e.g. photons [3] or neutrinos [4], two sectors could have a common gauge group of flavour [5] or common Peccei-Quinn symmetry [6].

A discrete symmetry $G \leftrightarrow G'$ interchanging corresponding fields of $G$ and $G'$, so called mirror parity, guarantees that two particle sectors are described by identical Lagrangians, with all coupling constants (gauge, Yukawa, Higgs) having the same pattern. As a consequence the two sectors should have the same microphysics. In the particular case in which $G$ sector is left-handed and $G'$ sector is right-handed, this discrete symmetry can be interpreted as the true parity [7].

[1] E-mail: `berezhiani@aquila.infn.it`
[2] E-mail: `ciarcelluti@lngs.infn.it`
[3] E-mail: `comelli@fe.infn.it`
[4] E-mail: `villante@fe.infn.it`

If the mirror sector exists, then the Universe along with the ordinary photons, neutrinos, baryons, etc. should contain their mirror partners. One would naively think that the O- and M-sectors, having the same microphysics, should have also the same cosmology.[1] Then one would expect that M-particles are present in the same amount in the Universe as O-ones, which would be in immediate conflict with the Big Bang Nucleosynthesis (BBN) bounds on the effective number of extra light neutrinos $\Delta N_\nu$: the mirror photons, electrons and neutrinos would give a contribution equivalent to $\Delta N_\nu \simeq 6.14$. However two sectors may have different initial conditions. In particular, after inflation, the two sectors could be reheated at different temperatures, $T'_R \neq T_R$, which can be achieved in certain inflationary models [8]-[11]. If the O- and M-particles interact weakly enough (which condition is automatically fulfilled if the two worlds communicate only via the gravity), the two systems do not come into thermal equilibrium at later epoch and they evolve independently, maintaining approximately constant the ratio $x = T'/T$ among their temperatures. The BBN constraints are satisfied if $x$ is sufficiently low. Namely, the most conservative bound $\Delta N_\nu < 1$ [12] implies that $x < 0.64$ [11].

The difference of the temperatures $T' < T$ breaks the symmetry between the cosmological properties of O- and M-sectors. Namely, the number density of M-photons is much smaller than that of O-ones, $n'_\gamma / n_\gamma = x^3 \ll 1$. It is important to understand, whether the mirror baryon density $n'_b$ could be comparable or even larger than the ordinary one $n_b$, in which case they could constitute dark matter of the Universe, or at least its significant fraction.

The cosmological evolution of the Mirror Universe was studied in ref. [11] and all the key epochs (baryogenesis, nucleosynthesis, recombination etc.) were analyzed in details. It was shown, in particular, that in the context of the GUT or electroweak baryogenesis scenarios the condition $T' < T$ yields that $\eta'_b \geq \eta_b$, where $\eta_b = n_b/n_\gamma$ and $\eta'_b = n'_b/n'_\gamma$ respectively are the baryon asymmetries in O- and M-sectors [11]. However, $\eta'_b/\eta_b \geq 1$ is not yet enough for having $\beta = n'_b/n_b \geq 1$. Since $\beta = x^3(\eta'_b/\eta_b)$, the latter requires much stronger condition $\eta'_b/\eta_b \geq x^{-3}$. As it was demonstrated in ref. [11], this condition can be satisfied for a certain range of parameters, with the values of $x$ which are not too low, $x \geq 0.01$ or so. However, more appealing situation emerges in a leptogenesis scenario due to particle exchange between the ordinary and mirror sectors suggested in ref. [13], which predicts $\beta \geq 1$ but also implies that $\beta < 10$ or so, and thus can explain naturally the near coincidence between the visible (O-baryon) matter density $\Omega_b$ and the dark (M-baryon) matter density $\Omega'_b$ in a rather natural way [2].

If $\Omega'_b \geq \Omega_b$, mirror baryons emerge as a possible dark matter candidate; they can contribute the dark matter of the Universe along with the cold dark matter or even constitute a dominant dark matter component. An immediate question arises: how the mirror baryon dark matter (MBDM) behaves and what are the differences from the more familiar dark matter candidate as the cold dark matter (CDM)?

The peculiar properties of mirror dark matter were discussed qualitatively in [11], and this analysis was confirmed and extended in refs. [14, 15]. In this paper we complete this program giving a complete quantitative presentation of the implications of the MBDM for the cosmological large scale structure (LSS) and the cosmic microwave background (CMB) anisotropies.

The plan of the paper is as follows. In the next section we analyze the relevant length scales for structure formation in the mirror photon-baryonic sector. In section 3 we describe the effect of the evolution of perturbations in linear regime and compute the power spectra for the LSS and CMB for various values of the two parameters $x$ and $\beta$. The main differences with respect to a standard CDM scenario are discussed. Finally, our main conclusions are summarized in section 4.

[1] More generically, M-parity could be spontaneously broken and the weak scales $\langle\phi\rangle$ and $\langle\phi'\rangle$ could be different, which would lead to somewhat different particle physics in the mirror sector [8].

## 2 Relevant length scales

Mirror matter may seem a tremendously complicated dark matter candidate. However, from the point of view of structure formation, it can be described relatively simply. The microphysics of the mirror sector is in fact well defined, being identical to that of our sector. All the differences with respect to the ordinary world can be described in terms of two macroscopic parameters which are the only free parameters in the model:

$$x \equiv \frac{T'}{T} \quad ; \qquad \beta \equiv \frac{\Omega'_b}{\Omega_b} \tag{1}$$

where $T$ ($T'$) is the ordinary (mirror) photon temperature in the present Universe,[2] and $\Omega_b$ ($\Omega'_b$) is the ordinary (mirror) baryon density fraction. In this section, we discuss the dependence of the length scales relevant for structure formation from these parameters.

In the most general context, the present energy density contains relativistic (radiation) component $\Omega_r$, non-relativistic (matter) component $\Omega_m$ and the vacuum energy density $\Omega_\Lambda$ (cosmological term). The present observational data indicate that the Universe is almost flat, i.e. $\Omega_0 = \Omega_m + \Omega_r + \Omega_\Lambda \approx 1$ in a perfect accordance with the inflationary paradigm, with $\Omega_m = 0.2 - 0.3$ and the rest of the energy density is due to the cosmological term. In the context of our model, the relativistic fraction is represented by the ordinary and mirror photons and neutrinos, $\Omega_r h^2 = 4.2 \times 10^{-5}(1 + x^4)$, where contribution of the M-species is negligible due the BBN constraint $x^4 \ll 1$. As for the non-relativistic component, it contains the O-baryon fraction $\Omega_b$ and the M-baryon fraction $\Omega'_b = \beta\Omega_b$, while the other types of dark matter, e.g. the CDM, could also present and so in general $\Omega_m = \Omega_b + \Omega'_b + \Omega_{\rm CDM}$.[3] In the following we use the central values by WMAP $\omega_b = \Omega_b h^2 \approx 0.023$ and $\omega_m = \Omega_m h^2 \approx 0.135$ [19], and consider scenarios with $\beta = 1 \div 5$ where the limiting case $\beta \simeq 5$ corresponds to the case when the dark matter is entirely due to MBDM ($\Omega_{\rm CDM} = 0$).

The important moments for the structure formation are related to the matter-radiation equality (MRE) and to the plasma recombination and matter-radiation decoupling (MRD) epochs. The MRE occurs at the redshift:

$$1 + z_{\rm eq} = \frac{\Omega_m}{\Omega_r} \approx \frac{3240}{1 + x^4} \left( \frac{\omega_m}{0.135} \right) \tag{2}$$

where we denote $\omega_m = \Omega_m h^2$. Therefore, for $x \ll 1$ it is not altered by the additional relativistic component of the M-sector.

The matter radiation decoupling takes place only after the most of electrons and protons recombine into neutral hydrogen and the free electron number density strongly diminishes, so that the photon scattering rate drops below the Hubble expansion rate. In the ordinary Universe the MRD takes place in the matter domination period, at the temperature $T_{\rm dec} \simeq 0.26$ eV which corresponds to redshift $1 + z_{\rm dec} = T_{\rm dec}/T_{\rm today} \simeq 1100$.

The MRD temperature in the M-sector $T'_{\rm dec}$ can be calculated following the same lines as in the ordinary one [11]. Due to the fact that in either case the photon decoupling occurs when the exponential factor in the Saha equation becomes very small, we have $T'_{\rm dec} \simeq T_{\rm dec}$, up to small logarithmic corrections related to $\eta'$, different from $\eta$. Hence

$$1 + z'_{\rm dec} \simeq x^{-1}(1 + z_{\rm dec}) \simeq \frac{1100}{x} \tag{3}$$

[2] The ratio of the temperatures between two sectors is nearly constant during the evolution of the Universe. In general, one has $T'/T = x[g_s(T)/g'_s(T')]^{1/3}$, where the factors $g_s$ and $g'_s$ accounting for the degrees of freedom of the two sectors can be different from each other, see ref. [11] for details.

[3] In the context of supersymmetry, the CDM component could exist in the form of the lightest supersymmetric particle (LSP). It is interesting to remark that the mass fractions of the ordinary and mirror LSP are related as $\Omega'_{\rm LSP} \simeq x\Omega_{\rm LSP}$. In addition, an HDM component $\Omega_\nu$ could be due to neutrinos with mass $\leq 0.3$ eV. The contribution of the mirror neutrinos scales as $\Omega'_\nu = x^3\Omega_\nu$ and thus it is irrelevant.

so that the MRD in the M-sector occurs earlier than in the ordinary one. Moreover, for a value $x = x_{\rm eq}$, where:

$$x_{\rm eq} = \frac{1+z_{\rm dec}}{1+z_{\rm eq}} \simeq 0.34 \left(\frac{0.135}{\omega_m}\right) \tag{4}$$

the mirror photon decoupling epoch coincides with the MRE epoch. This critical value plays an important role in our further considerations. Namely, for $x < x_{\rm eq}$ the mirror photons would decouple yet during the radiation dominated period.

Let us discuss now the relevant scales for evolution of perturbations in the MBDM. The relevant scale for gravitational instabilities is Jeans length, defined as the minimum scale at which, in the matter dominated epoch, sub-horizon sized perturbations start to grow. The mirror Jeans scale is given by:

$$\lambda'_{\rm J}(z) \simeq v'_s(z)\,(\pi/G\rho(z))^{1/2}\,(1+z) \tag{5}$$

where $\rho(z)$ is the matter density at a given redshift $z$, $v'_s(z)$ is the sound speed in the M-plasma and the $(1+z)$ factor translates the physical scale at the time of redshift $(1+z)$ to the present scale. We remark that the M-plasma contains more baryons and less photons than the ordinary one, $\rho'_b = \beta\rho_b$ and $\rho'_\gamma = x^4\rho_\gamma$, and thus the sound speed can have a quite different behaviour. We have:

$$v'_s(z) \simeq \frac{1}{\sqrt{3}}\left(1+\frac{3\rho'_b}{4\rho'_\gamma}\right)^{-1/2} \approx \frac{1}{\sqrt{3}}\left[1+\frac{3}{4}\frac{\beta\omega_b}{\omega_m}(1+x^{-4})\left(\frac{1+z_{\rm eq}}{1+z}\right)\right]^{-1/2} \tag{6}$$

where $\omega_b = \Omega_b h^2$, quite in contrast with the ordinary world, where $v_s \approx c/\sqrt{3}$ practically till the photon decoupling. The M-baryon Jeans length reaches the maximal value at $z = z'_{\rm dec}$, where it is given by [4]:

$$\lambda'_{\rm J,dec} \simeq \frac{100\,x^{5/2}}{(\beta\omega_b)^{1/2}(x+x_{eq})^{1/2}}\ {\rm Mpc} \tag{7}$$

After decoupling, eq. (6) does not hold anymore and the Jeans scale decreases to very low values, due to the fact that the pressure supplied by the relativistic component of the mirror plasma disappears.

Density perturbations in MBDM on scales $\lambda \geq \lambda'_{\rm J,dec}$ which enter the horizon at $z \sim z_{\rm eq}$ undergo uninterrupted linear growth immediately after $z_{\rm eq}$. Perturbations on scales $\lambda \leq \lambda'_{\rm J,dec}$ start instead to oscillate immediately after they enter the horizon, thus delaying their growth till the epoch of M-photon decoupling.

Finally, we turn our attention to dissipative processes which can modify the purely gravitational evolution of perturbations. As occurs for perturbations in the O-baryonic sector, also the M-baryon density fluctuations should undergo the strong collisional damping around the time of M-recombination. The photon diffusion from the overdense to underdense regions induces a dragging of charged particles and washes out the perturbations at scales smaller than the mirror Silk scale, $\lambda'_S$. The behavior of $\lambda'_S$ as a function of the parameter $x$ and $\beta$ is given by

$$\lambda'_S \simeq \frac{3\,f(x)}{(\beta\omega_b)^{3/4}}\ {\rm Mpc} \tag{8}$$

where $f(x) = x^{5/4}$ for $x > x_{\rm eq}$, and $f(x) = (x/x_{\rm eq})^{3/2} x_{\rm eq}^{5/4}$ for $x < x_{\rm eq}$.

The impact of such scales on the evolution of density perturbations will be discussed in the next section.

[4] We assumed $\beta x^{-4} \gg 1$ so that the constant term in eq. (6) can be neglected.

## 3 Evolution of perturbations

We clearly understand from the previous discussion that MBDM has peculiar features which can leave a characteristic imprint in the large scale structure of the Universe.

*First*, perturbations in MBDM on scales $\lambda \leq \lambda'_{\rm J,dec}$ experience an oscillatory regime. The MBDM oscillations transmitted via gravity to the ordinary baryons, could cause observable anomalies in LSS power spectrum and in the CMB angular power spectrum.

*Second*, for $x \geq x_{\rm eq}$, the growth of perturbations on scales $\lambda \leq \lambda'_{\rm J,dec}$ does not start at $z_{\rm eq}$ but is delayed till M-photon decoupling. If MBDM is the dominant dark matter component, one expect to observe less structures on these scales than in standard CDM scenario.

*Finally*, the density perturbation scales which can run the linear growth after the MRE epoch are limited by the length $\lambda'_S$. To some extent, the cutoff effect is analogous to the free streaming damping in the case of warm dark matter (WDM).

In order to make quantitative predictions we computed numerically the evolution of adiabatic perturbations in a Universe in which is present a significant fraction of mirror dark matter. More precisely, following the approach described in [17], we solved numerically in a synchronous gauge the linear evolution equations for perturbations of all matter components: ordinary baryons, photons, neutrinos, their mirror analogues, and cold dark matter. In fact, with respect to the standard case, the full set of equations was doubled in order to properly take into account the evolution of the mirror photon-baryon system. The decoupling in ordinary and mirror plasma was followed numerically as prescribed in [17]. All computations were made assuming a flat space-time geometry ($\Omega_0 = 1$; i.e. $\Omega_\Lambda = 1 - \Omega_m$). In order to compare our predictions with the "standard" CDM results, we have chosen a "reference cosmological model" with scalar adiabatic perturbations and no massive neutrinos with the following set of parameters [16]:

$$\omega_b = 0.023, \quad \omega_m = 0.133 \quad (\Omega_m = 0.25), \quad \Omega_\Lambda = 0.75, \quad n_{\rm s} = 0.97, \quad h = 0.73. \tag{9}$$

We have included in this model the mirror sector and studied the effects of MBDM as a function of the parameters $x$ and $\beta$. For the sake of comparison, in all calculations the total amount of matter $\Omega_m = \Omega_{\rm CDM} + \Omega_{\rm b} + \Omega'_{\rm b}$ was maintained constant, $\Omega_m = 0.25$. Mirror baryons contribution is thus always increased at the expenses of diminishing the CDM contribution. Hence, the case when dark matter is entirely represented by the MBDM, with no CDM component, corresponds to $\beta = \omega_m/\omega_b \simeq 5$.

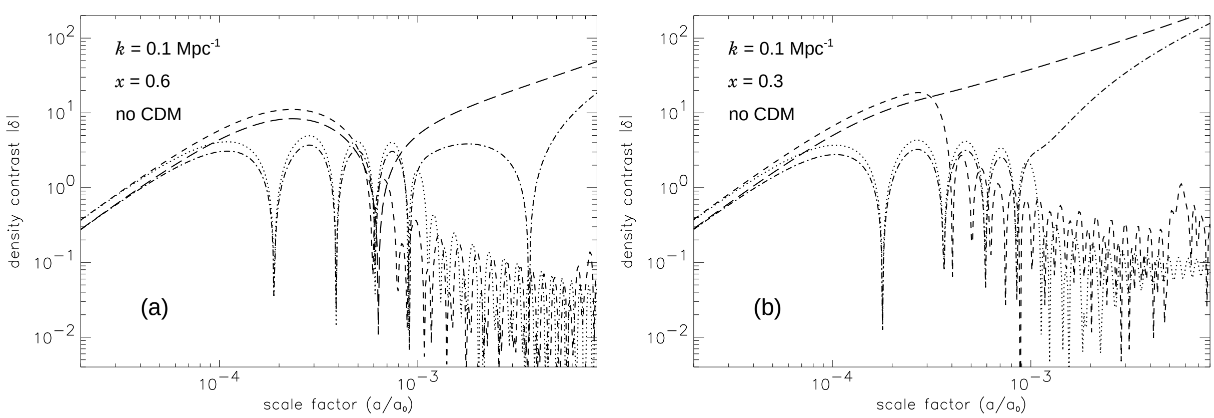


Figure 1: Evolution of perturbations at the scale $k = 0.1$ Mpc$^{-1}$ in the case when dark matter is entirely due to mirror baryons ($\Omega_{\rm CDM} = 0$). Dot-dashed and dotted lines correspond to ordinary baryons and photons, while long dashed and dashed lines are for mirror baryons and photons. All cosmological parameters are taken as in (9). Left panel (a) corresponds to the case $x = 0.6$ and the right panel (b) to the case $x = 0.3$.

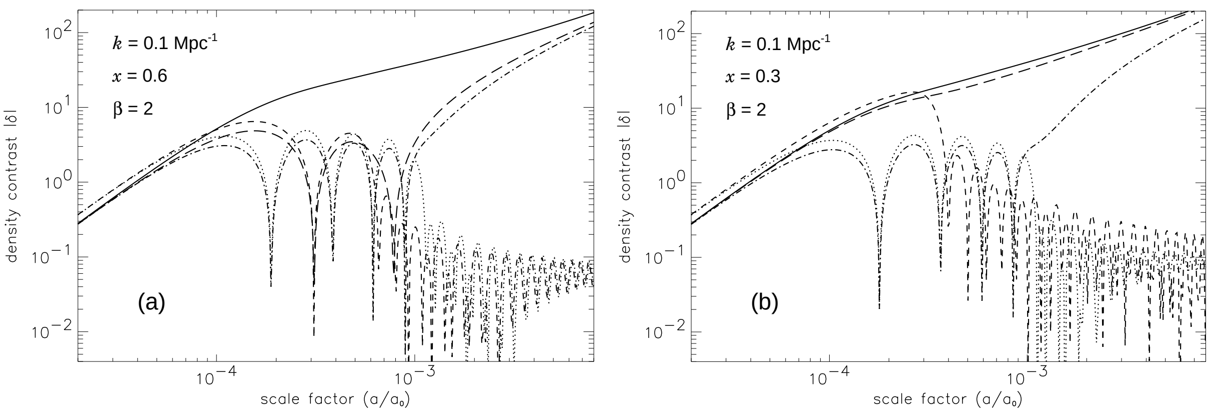


Figure 2: The same as in Fig. 1 but in the case when the MBDM is a sub-dominant dark matter component with $\beta = 2$, i.e. $\Omega'_b = 0.09$ and $\Omega_{\rm CDM} = 0.12$.

To understand the impact of mirror matter on structure formation it is useful to look at Fig. 1 and Fig. 2 where, for a selected wavenumber $k = 2\pi/\lambda$ and for selected values of $x$ and $\beta$, we show the evolution of the density contrast in the various components, $\delta_i = \delta\rho_i/\rho_i$, as a function of the scale factor $a$. In Fig. 1 we show the situation when dark matter is entirely due to mirror baryons, while in Fig. 2 mirror baryons represent a subdominant component. The panels (a) of the two figures are obtained by assuming large values of the mirror to ordinary temperature ratio (i.e. $x = 0.6$), while the panels (b) correspond to the value $x = 0.3$ which, for the chosen cosmological parameters, implies that M-photon decoupling approximately coincides with MRE epoch (c.f. eq. (4)).

As long as the perturbation scale is larger than the horizon, the various components grow at the same rate ($\delta_i \propto a^2$). The situation drastically changes when the perturbations enter the horizon (around $a/a_0 \sim 10^{-4}$). At this point, baryons and photons, for each sector separately, become causally connected and behave as a single fluid. In other words, we have two fluids, the ordinary baryon-photon and the mirror baryon-photon ones. The sub-horizon evolution of these fluids depends on the value of the Jeans lengths. If the Jeans length is larger than the perturbation scale then the photo-baryon fluid starts to oscillate. This is always the case (before the decoupling) for ordinary baryons and photons. This is not always true in the mirror sector. By comparing panels (a) and (b) of these two figures we see in fact that for large values of $x$ the M-photons and baryons oscillate, while for smaller $x$ values perturbations undergo uninterrupted growth even before M-photon decoupling (which occurs around $a/a_0 \simeq 10^{-3}x^{-1}$).

Oscillations in the mirror sector (when present), transmitted via gravity to the ordinary baryons, would produce observable anomalies in LSS power spectrum and in the CMB anisotropy spectrum. By comparing the late time perturbation evolution in Fig. 1a and Fig. 2a, we can understand that the efficiency of this process depends on the amount of mirror matter present in the Universe. After decoupling, in fact, baryons, which are no longer supported by photon pressure, rapidly fall in the potential wells created by the dominant dark matter component. If M-baryons dominate the dark matter budget, this leads asymptotically to $\delta_b = \delta'_b$ (see late time evolution in Fig. 1a). This means that the baryonic structure power spectrum re-write the M-baryonic power spectrum, which is suppressed at small wavelength due to Silk damping and is eventually modulated (if $x$ is not too small) as a results of acoustic oscillation. If instead CDM is the dominant dark matter component, we have asymptotically $\delta_b = \delta'_b = \delta_{\rm CDM}$ (see late time evolution in fig.2a), which means that both M-baryonic and O-baryonic structures will follow the "standard" CDM power spectrum.

The dependence of the LSS power spectrum on the parameters $x$ and $\beta$ is shown explicitly in Fig. 3. In the upper panel we assume that the dark matter is entirely due to mirror baryons

and we consider variations of the $x$ parameter. For large $x$ values, as a result of the oscillations in MBDM perturbation evolution, one observes oscillations in the LSS power spectrum. The position of these oscillations depends on $x$, as can be easily understood. The smaller is $x$ the smaller is the mirror Jeans scale at decoupling and thus the smaller are the perturbations scales which undergo acoustic oscillations. Superimposed to oscillations one clearly see the cut-off in the power spectrum due to the Silk damping. We remark that the Silk scale $\lambda'_s$ also depends on $x$ (and $\beta$), as it is described by eq. (8). As a consequence, the cut off in the power spectrum moves to smaller wavelength when we decrease the $x$ parameter.

In the lower panel of Fig. 3 we can appreciate the role of the parameter $\beta$. One clearly sees that, as expected, the smallest is the amount of mirror baryons the less evident are the features in the LSS power spectrum. Interestingly, for large $x$ values, one observes a relevant effect even for relatively small amount of mirror baryons; even for $\beta = 1$ the effects are quite noticeable.

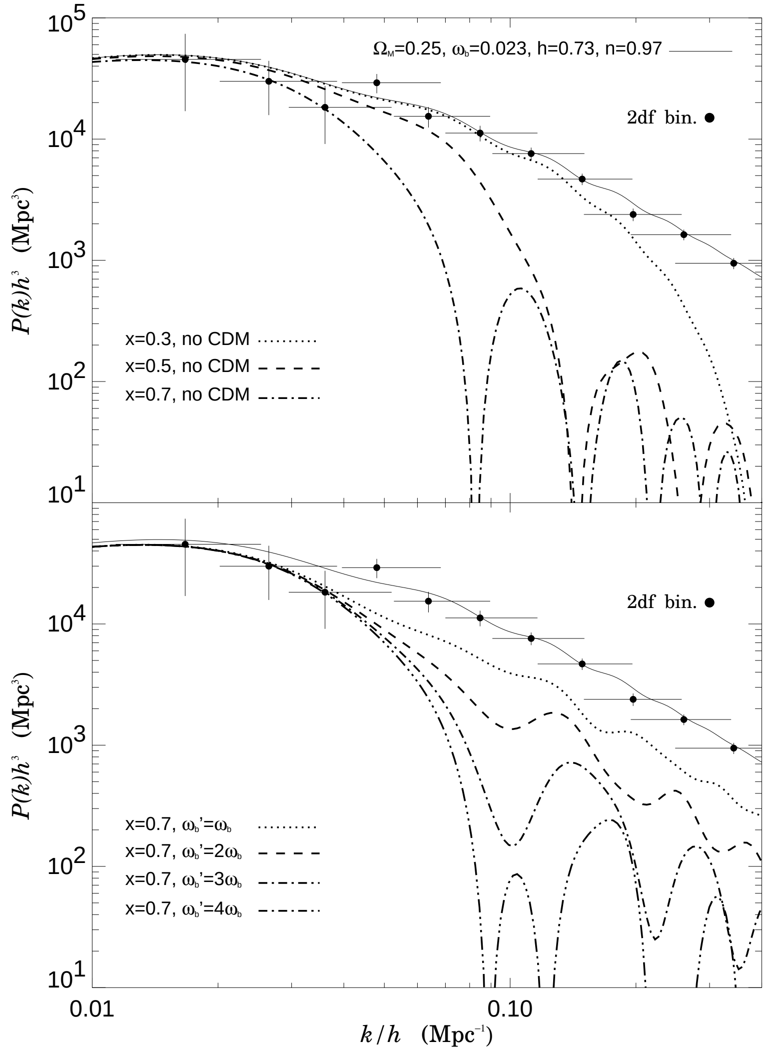


Figure 3: LSS power spectrum in the linear regime for different values of $x$ and $\omega'_{\rm b} \equiv \Omega'_{\rm b} h^2$, as compared with a standard model prediction (solid line). In order to remove the dependences of units on the Hubble constant, we plot on the x-axis the wave number in units of $h$ and on the y-axis the power spectrum in units of $h^{-3}$. All parameters are taken as in (9). We also show the binned data of 2dF observations [18]. *Top panel.* Models where dark matter is entirely due to MBDM (no CDM, i.e. $\beta = 5$) for different values $x = 0.3, 0.5, 0.7$. *Bottom panel.* Models with mixed CDM+MBDM components, $\beta = 1, 2, 3, 4$ for a value of $x = 0.7$.

Finally, in Fig. 4 we show the effects of MBDM on the angular spectrum of the CMB anisotropy. The predicted spectrum is quite strongly dependent on the value of $x$ (see upper

panel), and it becomes practically indistinguishable from the CDM case for $x < x_{\rm eq} \simeq 0.3$, in this case the MBDM behaves just as the CDM at the scales relevant for the CMB oscillations. However, the effects on the CMB spectrum rather weakly depend on the fraction of mirror baryons (see lower panel for different values of $\beta$). In other words, the CMB anisotropy spectrum is mainly sensitive to amount of extra-radiation in the Universe due to the the mirror sector (which is fixed by $x$, being $\Omega'_r \propto x^4$) but it can hardly distinguish between MBDM and CDM.

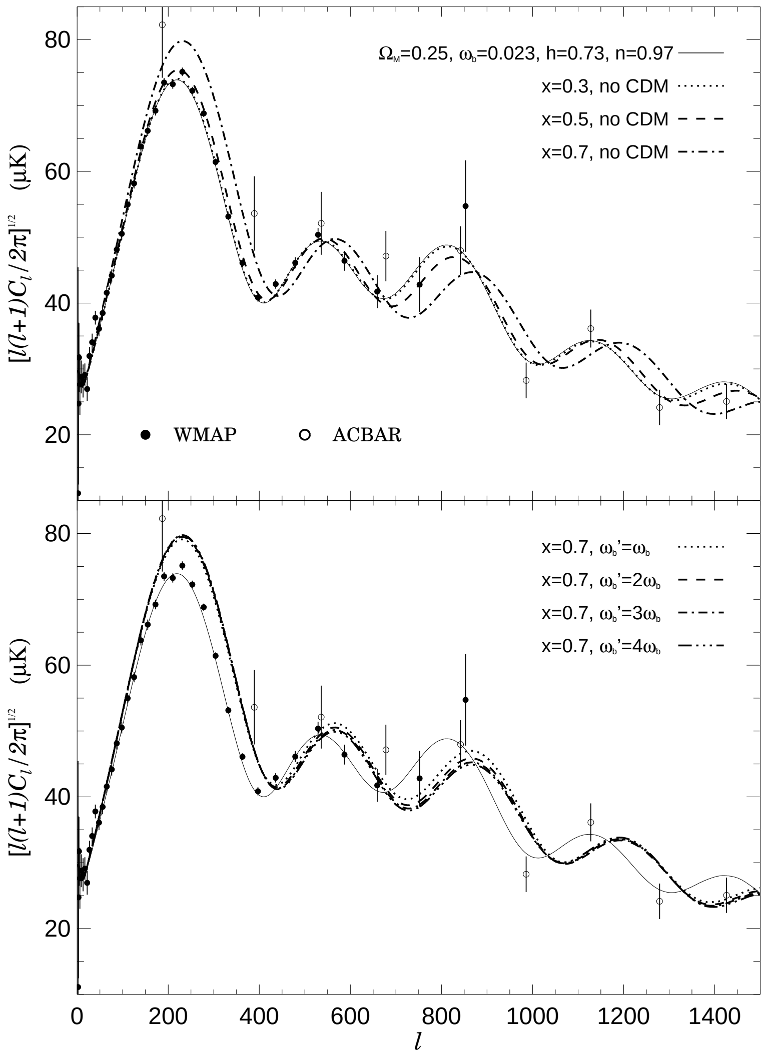


Figure 4: The CMB angular power spectrum for different values of $x$ and $\omega'_{\rm b}$, compared with a standard model (solid line). We also show the WMAP [19] and ACBAR [20] data. The choices of the parameters for both *top panel* and *bottom panel* exactly correspond to those of Fig. 3.

Our predictions can be compared with the observational data in order to obtain bounds on the possible existence of the mirror sector. To give a visual impression of the present situation we show in the Fig. 3 the 2dF binned data [18] and in Fig. 4 the WMAP [19] and ACBAR [20] data.

To extract information from the experimental data one clearly needs a detailed statistical analysis. However, some general conclusions can be obtained in a rather straightforward way:

(i) The assumption that DM is entirely due to mirror baryons is evidently not compatible with present LSS data unless the value of $x$ is enough small: $x < x_{\rm eq} \approx 0.35$.

(ii) Very high values of $x$, $x > 0.5$, can be excluded even for a relatively small amount of mirror baryons. E.g. for $x = 0.7$, one has relevant effects on LSS and CMB power spectrum down to values of M-baryon density of the order $\Omega'_b \sim \Omega_b$. On the other hand, intermediate

values $x = 0.3 - 0.5$ can be still allowed if the MBDM is a subdominant component of dark matter.

(iii) For small values of $x$, say $x < 0.3$, neither the linear LSS power spectrum nor the CMB angular power spectrum can distinguish the MBDM from the CDM. In this case, in fact, the Jeans length $\lambda'_{\rm J,dec}$ and the Silk length $\lambda'_S$, which mark region of the spectrum below which one sees the effects of mirror baryons, decrease to very low values, which undergo non linear growth from relatively large red-shift.

# 4 Conclusions

The idea of a mirror sector of particles and interactions has attracted a significant interest over last years. The concept of mirror world could have interesting implications for the following problems: detection of Machos via gravitational microlensing [8, 21], search ordinary-mirror star binaries [22] and mirror planetary objects [23], implications of mirror matter for galaxy halos [24], the role of the sterile neutrinos in neutrino physics [4, 25] and their implications for ultra-high energy cosmic rays [10] and gamma ray bursts [26], implications for the flavor and CP violation and axion physics [5, 6], etc. In particular, the effects based on the kinetic mixing among the ordinary and mirror photons [3, 27] can provide interesting possibilities for revealing the mirror matter in positronium decays [28] and in dark matter detectors [29].

In this paper, we have studied the cosmological implications of the mirror matter as dark matter. More precisely, we have quantitatively discussed the effect of the MBDM on the evolution of density perturbations in the linear regime as function of the two free parameters in the model: the temperature of the mirror plasma (limited by BBN to $x = T'/T < 0.64$) and the amount of mirror baryonic matter $\beta = \Omega'_b/\Omega_b$. We summarize here the main conclusions.

The concept of mirror baryons, as possible candidate for dark matter, introduces two new scales in the structure formation scenario: the Jeans scale of the mirror photo-baryon fluid, $\lambda'_{\rm J}$, and the Silk damping scale of mirror baryons, $\lambda'_{\rm S}$. Due to the pressure support of mirror photons, perturbations in the mirror fluid on scales smaller than $\lambda'_{\rm J,dec}$ cannot grow before mirror photon decoupling. If decoupling occurs after the MRE epoch (i.e. if $x \geq x_{\rm eq} \simeq 0.35$), and if mirror baryons are a relevant dark matter component, one expect then to see less structures on these scales with respect to the standard CDM scenario. In addition, mirror baryon perturbations on scales $\lambda \leq \lambda'_{\rm J,dec}$ go through an oscillatory regime. This could produce, via gravity, observable distortions in the CMB and LSS power spectrum. Finally, the mirror Silk scale $\lambda'_{\rm S}$ introduces a cut-off for the perturbation scales which can run the linear growth after matter-radiation equality.

All these effects were taken into account numerically in the Fortran code which we used to follow the perturbation evolution in presence of the mirror sector and to compute the LSS and CMB power spectra. The results are shown in Figs. 3 and 4 for various choices of parameters $x$ and $\beta$. From a comparison with present observational data, one is able to conclude that the existence of a mirror sector with a relatively high temperature, $T' \geq 0.4\ T$ and a high mirror baryon density $\Omega'_b \geq$ few $\Omega_b$ can be already excluded. This confirms previous estimates of refs. [11, 14] and improves the BBN bound on the mirror sector parameter space. More details can be found in ref. [15].

In order to further reduce the allowed parameter space, it would be clearly important to extend the analysis to the non-linear regime. Many relevant questions, related to the dynamics in this regime, can be formulated: what implications could have the mirror Silk cutoff for scales which already went non-linear, e.g. for scanning the early Universe via studying reionization, quasars, Lyman-$\alpha$ forest, etc.? Can mirror baryons, being a dissipative dark matter component, provide extended triaxial halos instead of being clumped into the galaxy as usual baryons? How the star formation mechanism proceeds in the M-sector where the temperature/density conditions and chemical contents are much different from the ordinary ones? Could the mirror

protogalaxy at a certain moment before disk formation become a collisionless system of the mirror stars and thus maintain a typical elliptical structure? What is the initial mass function of mirror stars, and how many and how heavy mirror stars do we expect as Machos in the galactic halo?

Many other questions can be formulated and various new data are needed to discriminate different cosmological settings. Our numerical analysis, which describes the mirror world in the linear regime, sets the starting point for answering these questions.


## Acknowledgements

We thank Silvio Bonometto, Stefano Borgani, Alfonso Cavaliere, Andrei Doroshkevic and Alessandro Melchiorri for interesting discussions. This work is partially supported by the MIUR research grant "Astroparticle Physics".


## References


[1] T.D. Li and C.N. Yang, Phys. Rev. 104 (1956) 254;
Y. Kobzarev, L. Okun, I. Pomeranchuk, Yad. Fiz. 3 (1966) 1154;
M. Pavšič, Int. J. Theor. Phys. 9 (1974) 229.

[2] For a review, Z. Berezhiani, hep-ph/0312335; to appear on Int. Journal Mod. Phys. A.

[3] B. Holdom, Phys. Lett. B166 (1985) 196;
S.L. Glashow, Phys. Lett B167 (1986) 35;
E.D. Carlson, S.L. Glashow, Phys. Lett. B193 (1987) 168.

[4] R. Foot, H. Lew, R. Volkas, Mod. Phys. Lett. A7 (1992) 2567;
E. Akhmedov, Z. Berezhiani and G. Senjanović, Phys. Rev. Lett. 69 (1992) 3013;
R. Foot, R. Volkas, Phys. Rev. D 52 (1995) 6595;
Z. Berezhiani, R.N. Mohapatra, Phys. Rev. D 52 (1995) 6607.

[5] Z. Berezhiani, Phys. Lett. B417 (1998) 287.

[6] Z. Berezhiani, L. Gianfagna and M. Giannotti, Phys. Lett. B500 (2001) 286;
see also V. Rubakov, JETP Lett. 65 (1997) 621.

[7] R. Foot, H. Lew, R. Volkas, Phys. Lett. B272 (1991) 67; Mod. Phys. Lett. A9 (1994) 169.

[8] Z. Berezhiani, A. Dolgov, R.N. Mohapatra, Phys. Lett. B375 (1996) 26;
Z. Berezhiani, Acta Phys. Polon. B 27 (1996) 1503.

[9] E. Kolb, D. Seckel, M. Turner, Nature 514 (1985) 415;
H. Hodges, Phys. Rev. D 47 (1993) 456.

[10] V.S. Berezinsky, A. Vilenkin, Phys. Rev. D 62 (2000) 083512.

[11] Z. Berezhiani, D. Comelli, F. Villante, Phys. Lett. B503 (2001) 362.

[12] E. Lisi, S. Sarkar, F.L. Villante, Phys. Rev. D 59 (1999) 123520;
F.L. Villante, A.D. Dolgov, hep-ph/0310138.

[13] L. Bento, Z. Berezhiani, Phys. Rev. Lett. 87 (2001) 231304; Fortsch. Phys. 50 (2002) 489; hep-ph/0111116.

[14] A.Y. Ignatiev, R.R. Volkas, Phys. Rev. D 68 (2003) 023518.

[15] P. Ciarcelluti, Ph.D. Thesis, astro-ph/0312607.

[16] D.N. Spergel et al., Astrophys. J. Suppl. 148 (2003) 175.

[17] C. Ma, E. Bertschinger, Astrophys. J. 455 (1995) 7.

[18] M. Tegmark, A.J.S. Hamilton, Y. Xu, MNRAS 335 (2002) 887.

[19] C.L. Bennett et al., Astrophys. J. Suppl. 148 (2003) 1.

[20] C.L. Kuo et al., astro-ph/0212289.

[21] Z. Silagadze, Phys. At. Nucl. 60 (1997) 272;
S. Blinnikov, astro-ph/9801015;
R. Foot, Phys. Lett. B452 (1999) 83;
R.N. Mohapatra, V. Teplitz, Phys. Lett. B462 (1999) 302.

[22] S. Blinnikov, M. Khlopov, Yad. Fiz. 36 (1982) 675; Sov. Astron. 27 (1983) 371;
M. Khlopov et al., Astron. Zh. 68 (1991) 42.

[23] R. Foot and Z.K. Silagadze, Acta Phys. Polon. B 32 (2001) 2271;
R. Foot, A. Ignatiev and R.R. Volkas, Astropart. Phys. 17 (2002) 195;
R. Foot, S. Mitra, Astropart. Phys. 19 (2003) 739.

[24] R.N. Mohapatra, V. Teplitz, Astrophys. J. 478 (1997) 29; Phys. Rev. D62 (2000) 063506;
R.N. Mohapatra, S. Nussinov and V.L. Teplitz, Phys. Rev. D66 (2002) 063002; *ibid.* D68 (2003) 023518.

[25] R. Foot, R.R. Volkas, Phys. Rev. D61 (2000) 043507;
V. Berezinsky, M. Narayan, F. Vissani, Nucl. Phys. B658 (2003) 254.

[26] S. Blinnikov, astro-ph/9902305;
R. Volkas, Y. Wong, Astropart. Phys. 13 (2000) 21.

[27] R. Foot, A. Ignatiev, R.R. Volkas, Phys. Lett. B503 (2001) 355.

[28] S.N. Gninenko, Phys. Lett. B326 (1994) 317;
R. Foot, S. Gninenko, Phys. Lett. B480 (2000) 171;
A. Badertscher et al., hep-ex/0311031.

[29] R. Foot, hep-ph/0308254; astro-ph/0309330.